Analysis and removal of multiply scattered tube waves

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SUMMARY

Due to irregularities in or near the borehole, VSP or crosswell data can be contaminated with scattered tube waves. This type of organized noise can not always be removed with filtering methods currently in use. We propose a method, based on a one-dimensional impedance scattering model, for suppressing scattered tube waves. This method also accounts for multiply scattered tube waves. We apply the method to an actual VSP dataset and conclude that the continuity of reflected events is improved significantly in a washout zone.

INTRODUCTION

In many VSP or crosswell datasets, tube waves are the major source of coherent noise, leading to difficulty in separation of the reflected wavefield. For suppressing the direct tube wave, multichannel filters can be used (see, for instance, Houston , 1992). Apart from the direct tube wave, however, scattered tube waves can also be present. Scattering of tube waves can be caused by irregularities in the diameter of the borehole like washout zones or by cross-sectional area changes in the borehole fluid column. In addition, lithology changes in the formation adjacent to the borehole can also cause scattering of tube waves. Experimental techniques for reducing the scattered tube waves have been suggested by Milligan et al. (1997). In the case of large washout zones, however, these experimental methods are not always sufficient. In the present paper, a processing technique is suggested for reducing the effect of scattered tube waves. The theoretical basis of the method is a simple but effective one-dimensional scattering model of the borehole scattering process.

A model study of tube-wave scattering. Before describing the method for suppressing the scattered tube waves, we first consider the tube-wave scattering problem in somewhat more detail with the aid of a modeling study. We consider a cross-hole geometry with the source at a distance of 21 m from the receiver well. In the receiver well, a washout zone is present having a vertical extent of 3 m, where the diameter of the borehole changes abruptly from 0.073 m to 0.1 m.

The compressional wave speed, v_P, is 3,800 m/s, the density is 2 g/cc, the wave speed in the fluid of the receiver borehole is 1,500 m/s and the shear wave speed v_S satisfies the relation v_S = 0.6 v_P. With the aid of the bidomain finite-difference modeling method of Dong and Rector (1997) we have computed the pressure at various depths in the receiver well. The result is shown in figure 1.

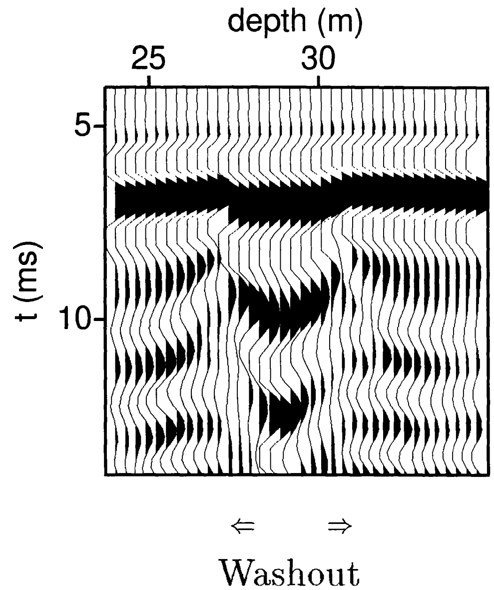

Figure 1: Arrival of the direct wave for a simulated crosswell experiment in the region around a washout zone. A significant amount of scattered tube waves is generated that remains trapped in the washout zone for a while and therefore cause a severe distortion of the incoming wave.

This figure shows the direct compressional wave in the region around the washout zone. Even though the diameter change is very small when compared to the wavelength, a significant amount of tube-wave scattering is caused by the two discontinuities at either side of the washout zone. The tube waves, originated in this way, remain trapped in the washout zone for a while causing a major distortion of the direct arival. The linear tube-wave events outside the washout zone can be reduced with the aid of multichannel filters, but the horizontal event in the washout zone itself can not be removed in this way without affecting the direct wave. Apart from the direct wave, upcoming reflected waves can also be distorted in a similar way by scattered tube waves within the washout zone. The method to be discussed in the present paper mainly aims at removing this type of scattering effect. As is apparent from figure 1, the scattered tube waves are not weak with respect to the first arrival and can bounce a few times within the washout zone before they have been attenuated sufficiently. This implies that multiple scattering of the tube wave preferably has to be taken into account.

DESCRIPTION OF THE METHOD

The theoretical basis of the method is a simple but effective one-dimensional scattering model of the borehole scattering process. It has been shown by Tezuka et al. (1997), that this type of method is accurate if the borehole diameter is small with respect to the seismic wavelengths involved, a condition that is satisfied for the frequencies used in VSP and many crosswell applications.

We decompose the pressure p, recorded in the borehole, in the following way:

$$p(z,\omega) = p^0(z,\omega) + p^1(z,\omega), \tag{1}$$

where p^0 is the undisturbed pressure we would have measured in the absence of borehole defects, and p^1 is the field scattered by such defects. According to the one-dimensional scattering model, the scattered field p^1 can be expressed as

$$p^1(z,\omega) = \int_{\text{borehole}} g(z-z',\omega)\,\sigma(z',\omega)\,p(z',\omega)\,dz', \tag{2}$$

where g is the tube-wave part of the Green's function and σ is the borehole scattering impedance. In this way, all scattering processes are "lumped" at the borehole axis. Since g only accounts for the fundamental mode of the Stoneley wave, often termed tube wave, it is simply the scalar one-dimensional Green's function with the tube-wave velocity. The tube wave is trapped inside the borehole and has no spherical spreading. The method is based on isolation of the first arrival of the wavefield and use of this first arrival to obtain an estimate of the borehole scattering impedance σ. After obtaining the impedance function from the first arrival, it can then be used to predict and subtract the scattered total field p^1. We note that, since Eqs.(1)-(2) are not based on the Born approximation, **multiply scattered tube waves are also taken into account.**

APPLICATION TO ACTUAL VSP DATA

The data was recorded with a weight-drop source situated at a distance of 72 m from the receiver well. There were 146 hydrophone channels with a vertical spacing of about 0.5 m; the upper hydrophone was at a depth of 79 m. Apart from the fact that the subsurface around the well was very complex, the dataset had the additional difficulty of scattered tube waves. In figure 2, a detail of the VSP is shown. In the area between 90 m and 96 m deep, there are scattered tube waves present, probably caused by a washout zone. After applying a frequency-wavenumber fan filter removing all slopes equal or larger than the slope of the tube wave and suppressing the downgoing direct arrival with the aid of a constrained eigenvector method (Mars and Rector, 1995), we obtain the result shown in figure 3. In the washout zone, remnants of the tube-wave apex are visible. The tube-wave remnants are confined principally to the washout zone and are smeared by the repeated spatial filtering. They are interfering with the upcoming waves and therefore destroying the continuity of reflections in the washout zone. We applied our method of tube-wave suppression, discussed in the previous section, to this dataset. In the first step, the direct arrival (including the scattered part) is separated with the aid of a time window having a width of about 20 ms. Then, a narrow frequency-wavenumber filter is applied in order to retain only the linear part of the direct arrival. The result of this process is assumed to be the "undisturbed" direct arrival, that we would observe in the absence of the washout zone. After subtracting it from the actual windowed first arrival, we obtain

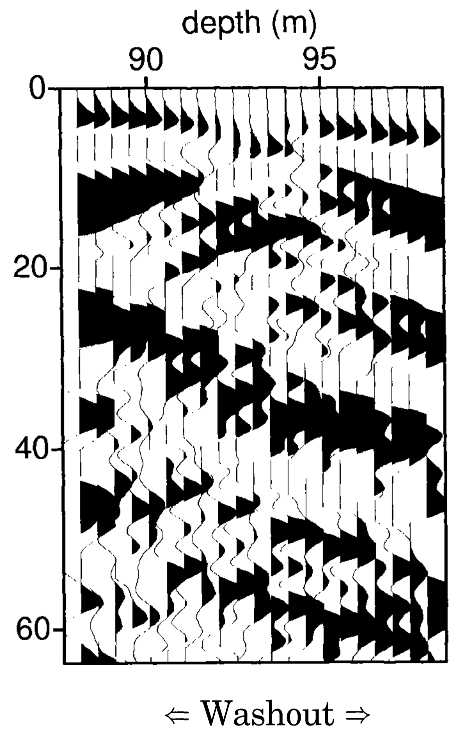

Figure 2: Detail of the VSP. Between 90 m and 96 m depth, there is a significant amount of scattered tube waves present probably caused by a washout zone.

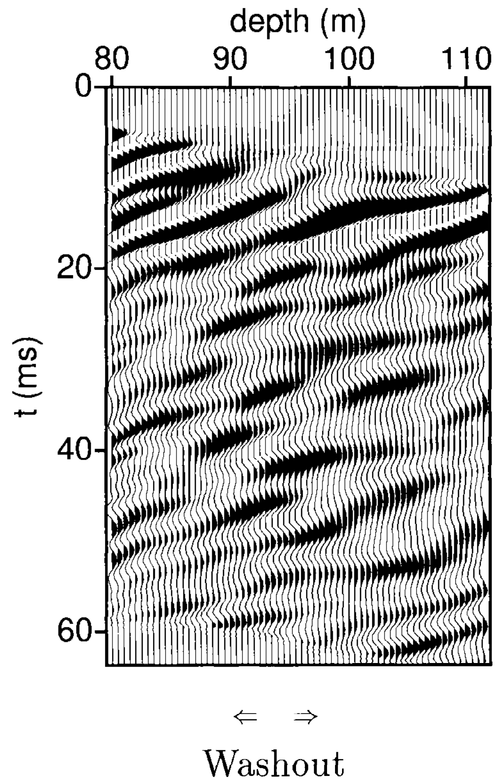

Figure 3: Result after suppressing the downgoing direct arrival from the data shown in figure 2. In the washout zone, remnants of the apex are visible in the form of events that are mainly present in this region and are smeared out by the repeated application of spatial filtering methods.

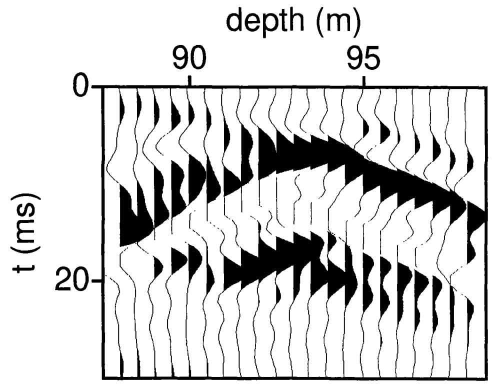

Figure 4: Our estimate of the scattered first arrival.

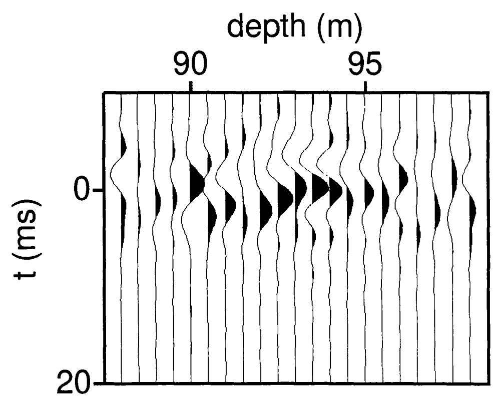

Figure 5: Borehole scattering impedance $\sigma(z, t)$, obtained after applying a temporal inverse Fourier transfrom to $\sigma(z, \omega)$.

our estimate of the scattered first arrival. This scattered first arrival, shown in figure **4,** can be used for estimating the borehole scattering impedance $\sigma(z, \mathrm{w})$. First, the product σ p is determined by spatially convolving the scattered direct arrival with the inverse of the tube-wave Green's function g. The value of $\sigma(z, \mathrm{w})$ is then obtained after a temporal deconvolution (or spectral division) for the actual downgoing wavefield first arrival present in p. The result for σ obtained in this way is shown in figure 5. When comparing this with the scattered field of figure 4, it indeed seems more "focused". After the impedance distribution has been obtained from the direct arrival, we can apply it to estimate the **total** scattered field by evaluating the right-hand side of Eq.(2). By subtracting this estimate from the total field p, we obtain the undisturbed field p^0, which would have been observed in the absence of the washout zone. In figure 6, the result is shown after removing the estimated scattered wavefield p^1, followed by the same direct wave separation sequence that was used to create figure 3. When we compare figure 6 with figure 3, we observe that the "wormy" interference patterns between 90 m and 96 m depth have been reduced whereas the continuity of upcoming events seems to have improved in figure 6. The remaining interference patterns are probably due to the interference of events of different dip caused by the rather complex geology around the well.

CONCLUSIONS

In this paper, we present a method for reducing the effect of scattered tube waves. It is based on the following assumptions:

1. Tube-wave scattering and conversion of P- and S-waves into tube waves can be described by a one-dimensional impedance model. This implies that the scattering process has to take place close to the borehole.

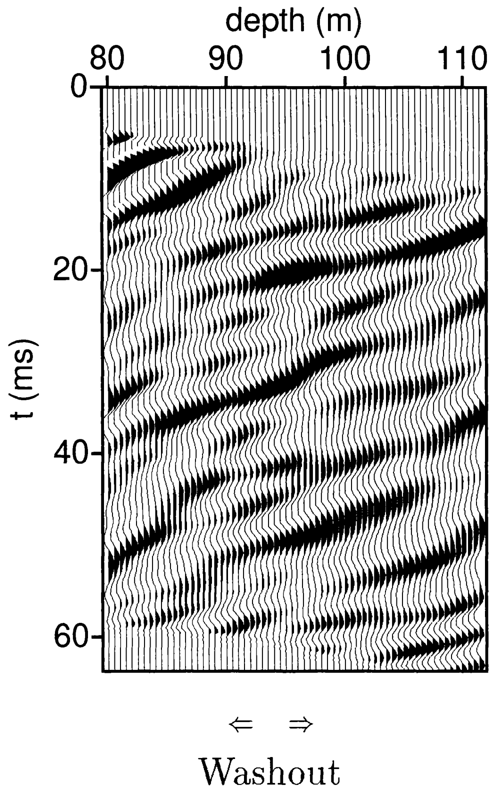

Figure 6: Upcoming reflections after the same processing sequence as in figure 3, but with subtraction of the estimated scattered wavefield p^1 before suppression of the downgoing direct arrival. The effects due to the washout zone have been reduced.

2. The scattered tube waves are the dominant part of the scattered wavefield

3. The direct arrival is separated in time from the upcoming reflections. This means that terminations of reflections, that are interfering with the direct arrival, can in principle be attenuated by applying this method. We have observed this effect in our final results shown in figure 6. All deeper reflections below the 20 ms modeling window, however, are treated correctly.

The impedance method discussed in this paper is not based on the Born approximation and therefore can take multiple tube-wave scattering into account. This seems necessary, since the Born approximation does not seem to be valid when scattered tube waves are strong enough compared to the total wavefield to be re-scattered multiple times (see figure 1). The method has been validated for synthetic data and tested on an actual VSP dataset. It appears to reduce the effect of mainly the apex of the scattered wavefield which can not be removed with the aid of conventional frequency-wavenumber filtering techniques or the like.

The near-receiver scattering problem considered here shows a remarkable resemblance to the near-subsurface "statics" problem. Since shallow scattering problems can also be cast into a scattering-impedance formulation, one could apply a similar formalism to resolve near-receiver scattering effects also known as "short-wavelength" statics (mutatis mutandis), and again a similar method for resolving the near-source effects. Instead of the tube-wave part of the Green's function, one would probably need the Rayleigh-wave part.

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